Report No. TR-4031

# ROCK DISINTEGRATION BY LIQUID JETS



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## SEMIANNUAL REPORT



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# I. OBJECTIVES AND SCOPE

The object of the research program is to optimize the efficiency of rock disintegration by pulsed high pressure water jets. Experiments are to be conducted on the splitting of hard rocks including granite by pulsed cumulative water jets with jet stagnation pressures up to one million psi. The high energy pulsed jets are to be produced using Voitsekhovsky-type nozzles (U.S. patent 3,343,794). The experimental data are to be correlated in terms of dimensionless parameters. The test objective is to determine the jet parameters which minimize the energy required per unit volume of rock broken. The jet impact pattern which maximizes the "split-off" volume is to be determined with one cubic foot rock samples.

## II. MAJOR ACCOMPLISHMENTS

A. Program Plan. During January, 1971, a program plan was developed and submitted. The milestones in this plan for the first half of the program have been accomplished with the exception of delivery of the nozzle and subsequently the completion of the test rig assembly. The completed milestones are discussed in the following paragraphs in this section. The milestones programmed for the second half of the program are discussed in Section IV, Future Plans.

B. Nozzle Design. The exponential nozzle is similar to that of Professor Voitsekhovsky and has an entrance diameter of 2.125 inch, an exit diameter of 0.238 inch and a length of 38.6 inches. Water will be extruded through the nozzle by impact of a metal piston of 3.25 inch diameter and a weight of 6.3 pounds, impacting at a maximum velocity of 740 ft/sec. Thus the maximum impact energy is 53,500 foot-pounds. Figure 1 is a simplified cross sectional view of the nozzle assembly showing the nozzle diameter at each transition point. The exponential nozzle function is closely approximated by a series of core sections for ease of manufacture. Sections

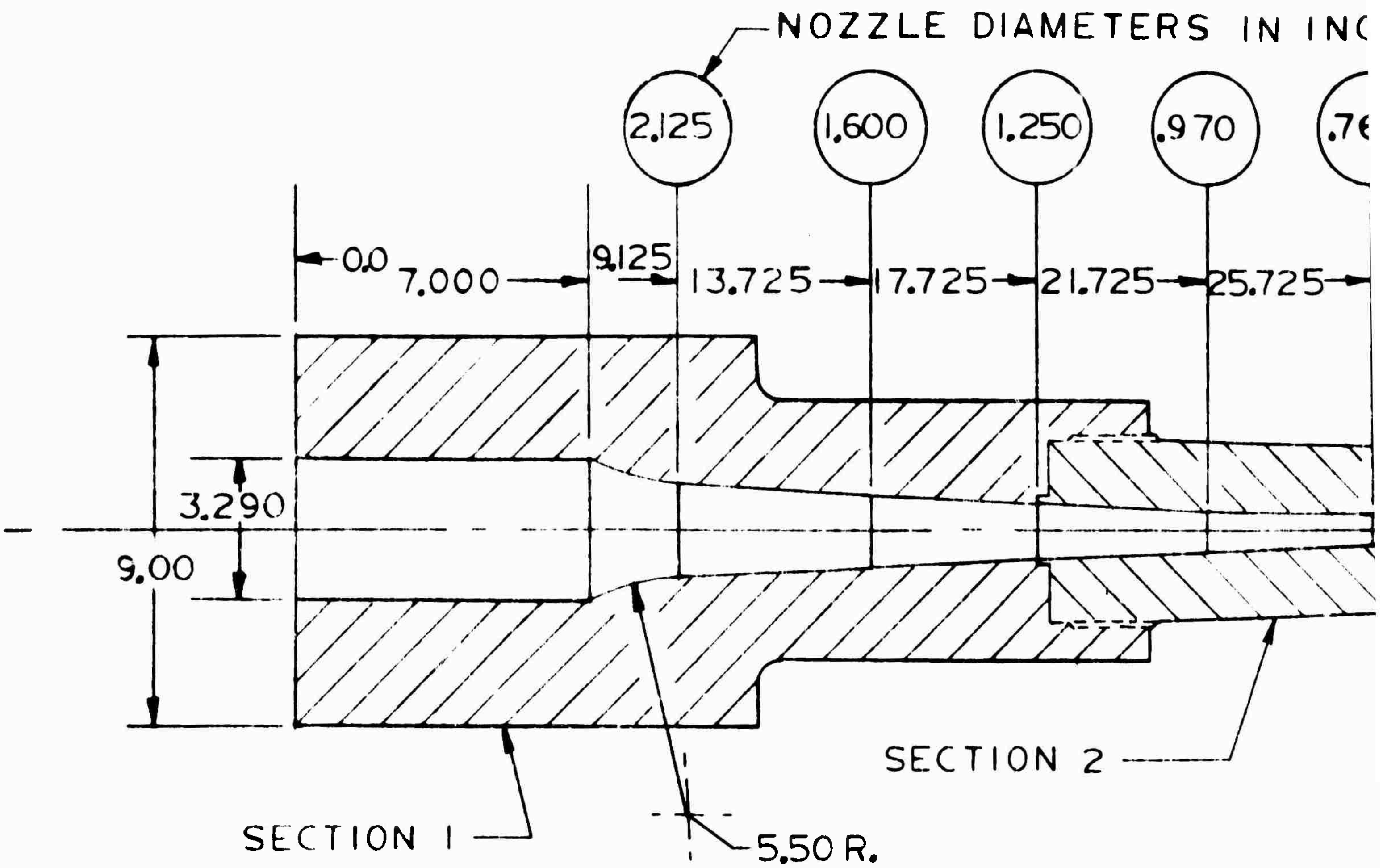
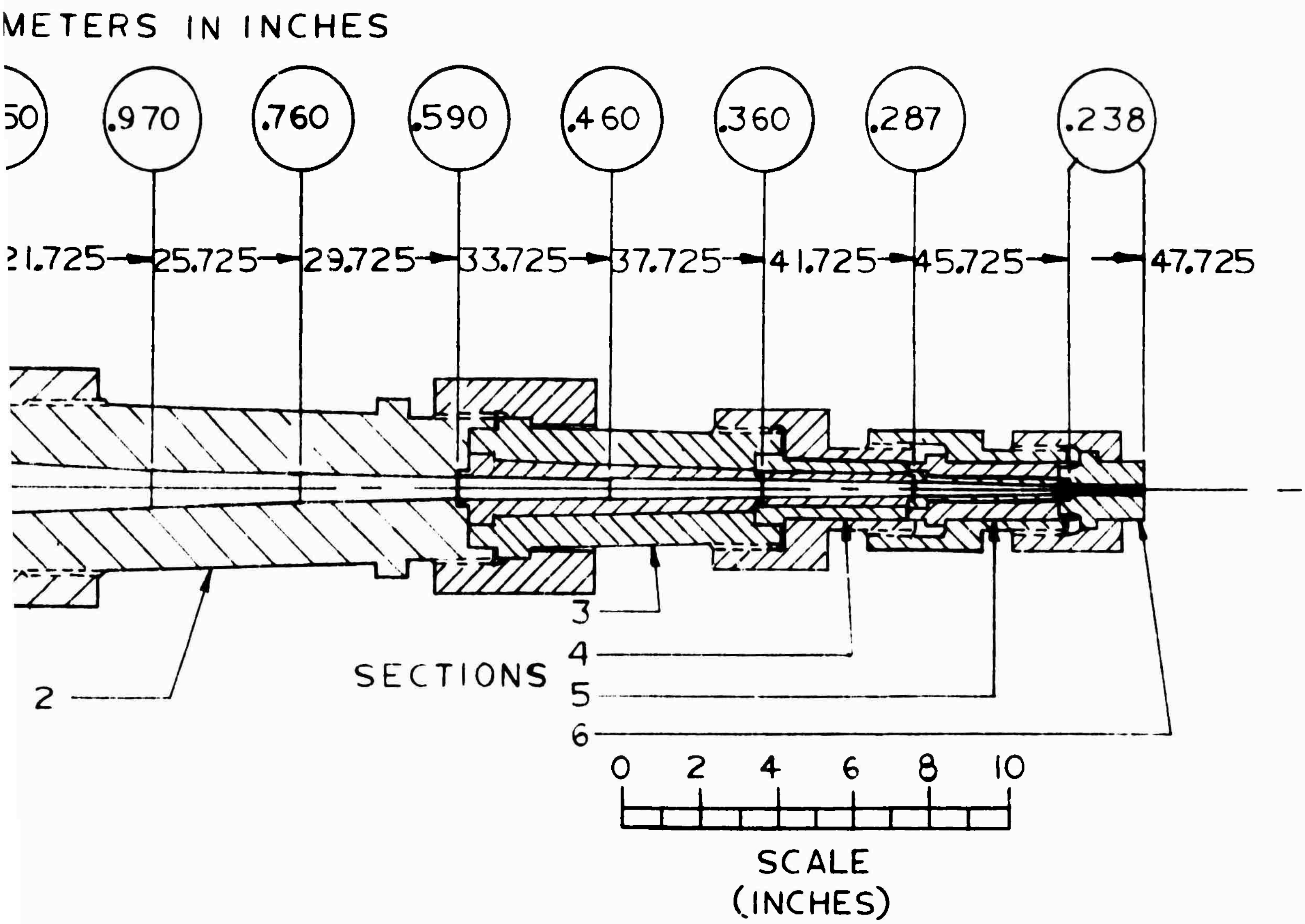



FIGURE 1. NOZZLE ASSE




NOZZLE ASSEMBLY

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3, 4, and 5 are double walled with the inner section being compressively prestressed. Section 6 is a constant diameter nozzle with an L/D ratio greater than 6/1 for final jet shaping.

C. Actuator Design. Several design approaches were considered before arriving at the final air gun design. One actuator design was considered which would drive a piston of about 6 to 7 inch diameter. It would have used an enclosed volume of compressed nitrogen for energy storage and an oil hydraulic cylinder to cock the actuator. The advantages of such an actuator would be:

1. Lower operating cost per shot because compressed gas is not lost with each shot.

2. Closer simulation of the Voitsekhovsky test conditions (which used a 6.3 inch piston) so that nozzle performance would be more predictable.

3. A more compact design with less problem of alignment of the actuator with the nozzle and high pressure cylinder.

4. Less time required between successive test shots.

5. Flexibility for ultimate conversion to a water cannon with more rapid repetitive firing capability.

Cost estimates on the fabrication of this closed-cycle actuator showed that the costs were prohibitive.

Therefore the program is being implemented by using a surplus air gun as the actuator. The air gun was purchased by Terraspace as capital equipment and was installed in the laboratory as shown in Fig. 2. A close-up view of the control console is shown in Fig. 3.

The air gun has a barrel length of 16 feet 8 inches with a bore diameter of 3.25 inches. Although referred to as an "air" gun, it will be actuated by compressed nitrogen which is loaded into a 550 cubic inch reservoir at pressures up to 2200 psi. (Inert nitrogen is used to avoid explosion hazard with any oil which may be in the system). The piston is initially located in the breech at a position which prevents high pressure gas from entering radial ports in the barrel. In order to fire the piston, compressed gas is introduced to move the piston a small distance, then compressed gas enters through the ports behind the piston and accelerates it in the barrel until it impacts a volume of water in the nozzle assembly. The water will be held in place by a plastic or rubber container.

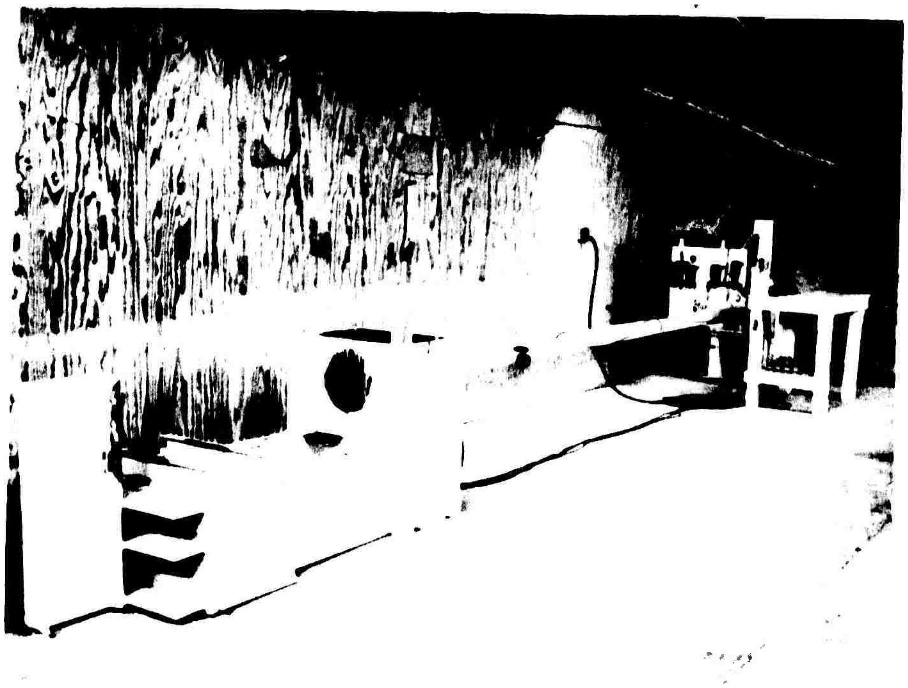

Figure 2. Air Gun

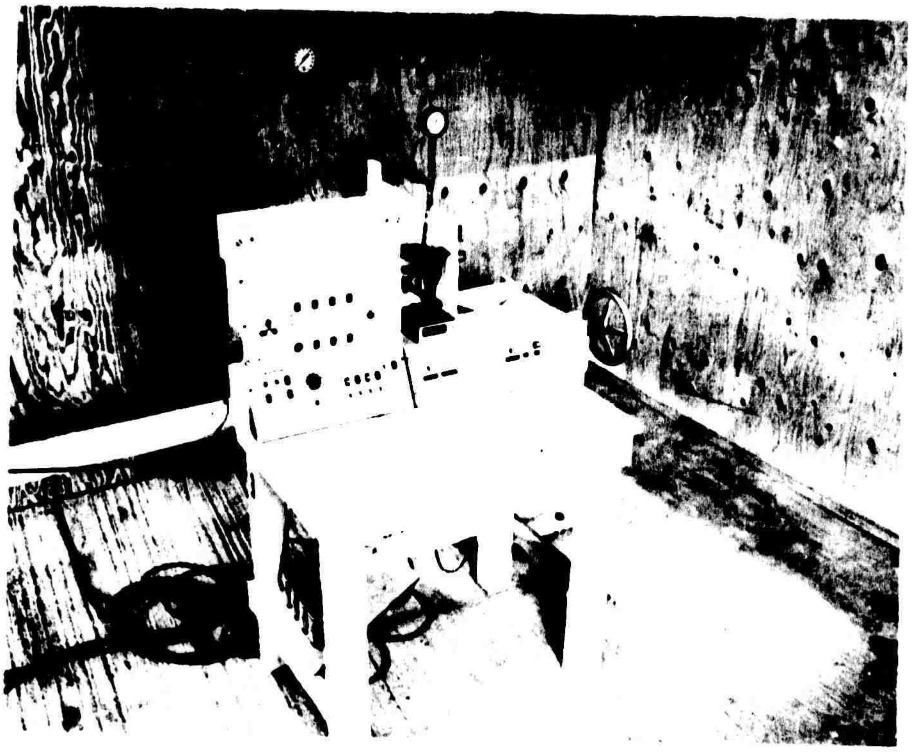

Figure 3. Air Gun Control Console

D. Test Rig Design. The air gun muzzle support section was redesigned to incorporate a nozzle support section, provision for crushable material to absorb the energy not absorbed by the water in the nozzle, and a platform for the rock samples. The test rig design, with the nozzle in place, is shown in Figure 4.

E. Procurements. The following equipment has been procured (or ordered) as Terraspace capital equipment for use on this contract:

Air gun
Heavy duty lift table
Vacuum pump, Lammert 10202
Time interval meter, Eldorado 255
Oscilloscope, Tektronix 502A
Oscilloscope camera, Tektronix C30A-P
Pressure Transducer, Kistler 207C3
Battery Coupler, Kistler 549

Five steel pistons were procured for use in the air gun. Orders have been placed for the following equipment chargeable to the contract:

Nozzle assembly
Nozzle support assembly
Balsa wood (crushable material)

Orders were placed for an initial supply of rock samples as follows:

5 One-foot cubes Barre Granite
1 Four-inch cube Barre Granite
5 One-foot cubes Indiana Limestone
1 Four-inch cube Indiana Limestone
5 One-foot cubes Berea Sandstone
1 Four-inch cube Berea Sandstone
(The four-inch cubes are for compressive strength tests).

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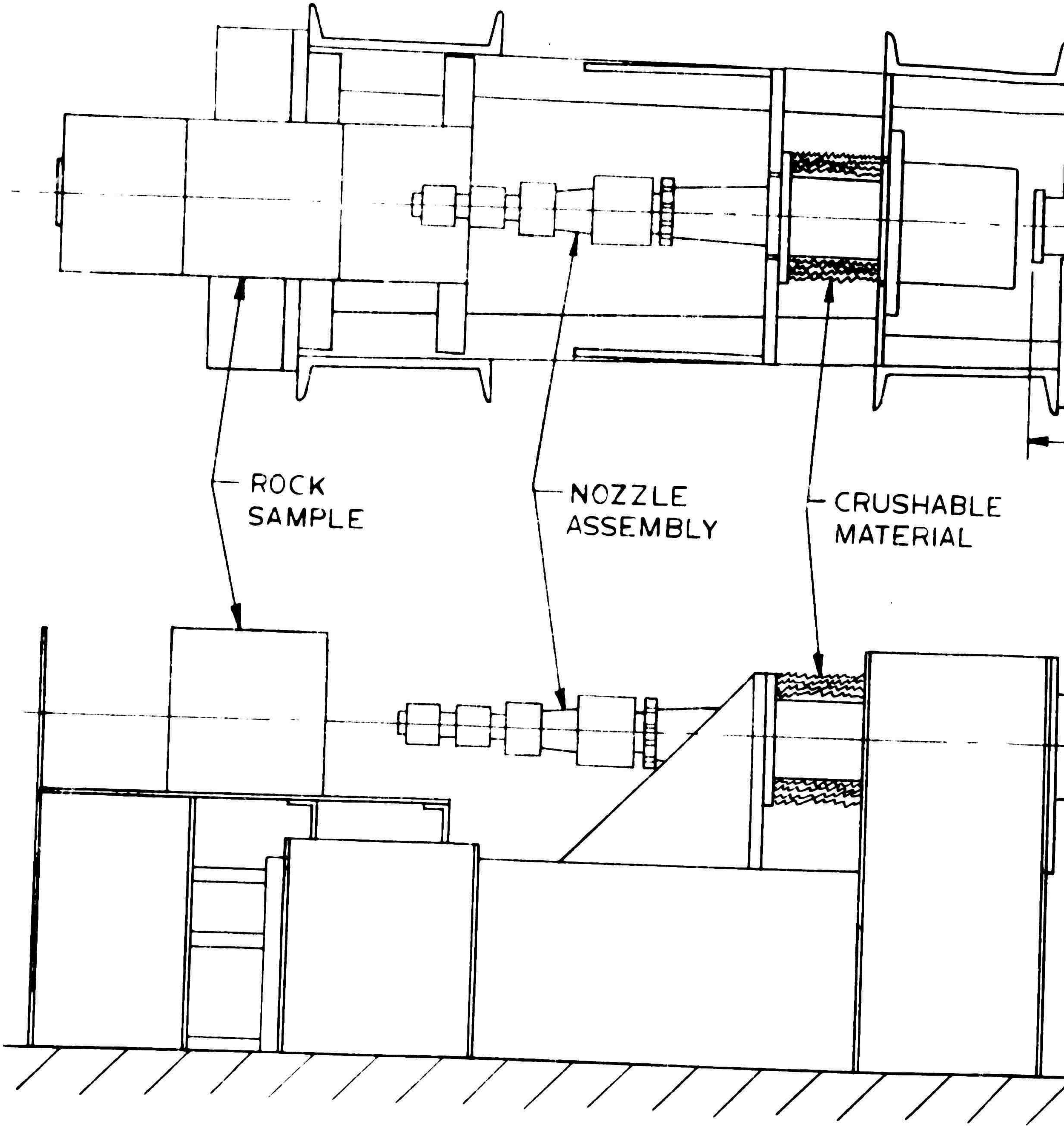
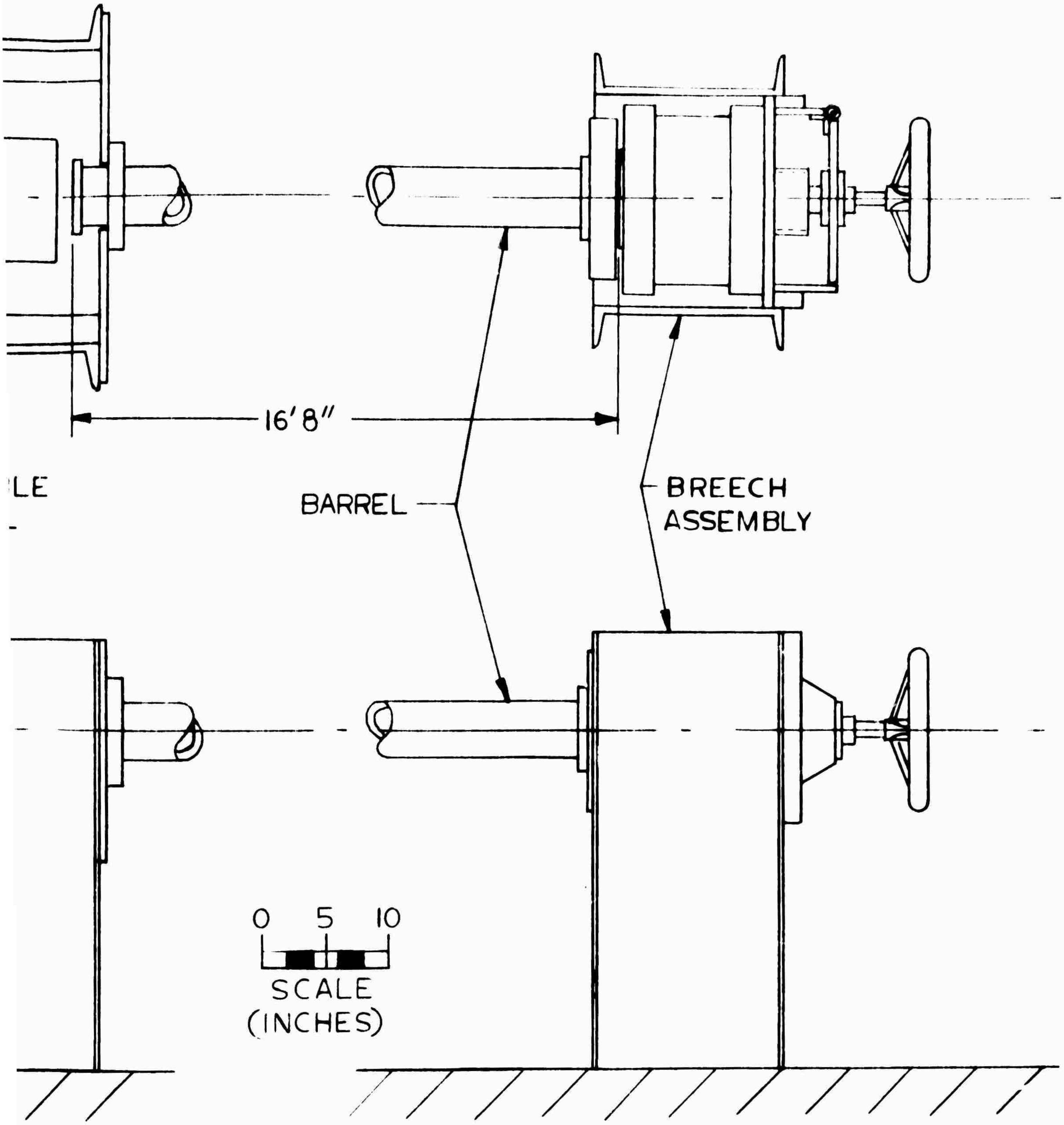



FIGURE 4. TEST R




TEST RIG ASSEMBLY



B

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F. Actuator Calibration. The air gun was installed in the Terraspace laboratory, aligned, instrumented and checked out. Calibration shots were made firing the piston into styrofoam energy absorbing material.

Based on recommendations of the former operator of the air gun, and on O-Ring handbook data, the piston was designed to use Teflon O-Rings of 0.210 inch cross sectional diameter. It was discovered that the high compressive force resulting from the high hardness of the Teflon more than offset the low frictional coefficient. In addition, the Teflon rings are very difficult to install and do not flow easily to seal at low pressure differentials. Several attempts to fire the piston with Teflon O-Rings were unsuccessful because of leakage.

A piston was then fitted with 0.210 inch Neoprene O-Rings and fired successfully with the following results, which are plotted in Figure 5, as curve "A."

| Pressure $lb/in^2$ | Velocity ft/sec |
|---|---|
| 100 | 80 |
| 150 | 190 |
| 200 | 242 |
| 250 | 290 |
| 300 | 308 |

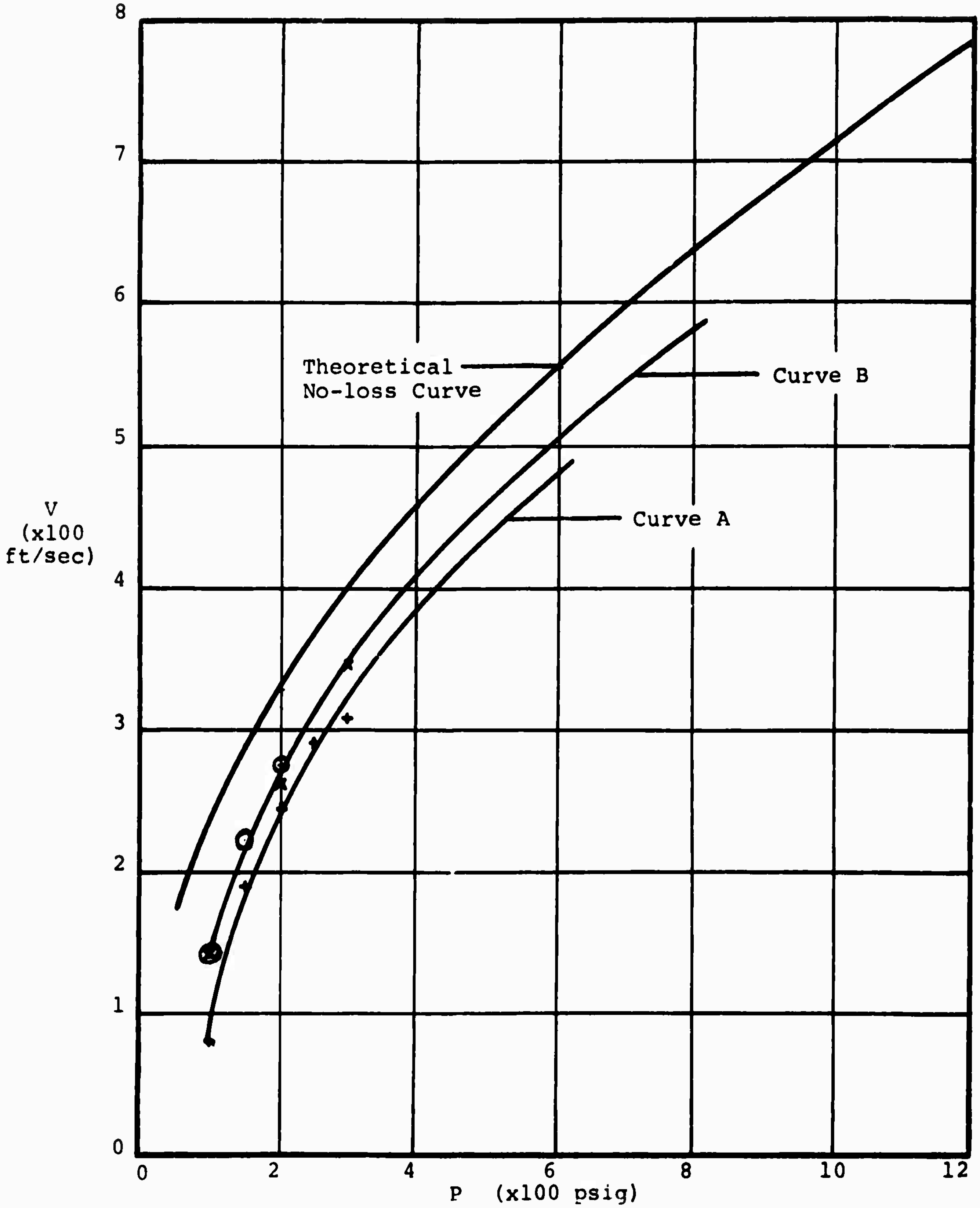


Figure 5. Air Gun Calibration

A second series of firings was made with the gun barrel evacuated to a pressure of less than 0.1 inch of mercury. The muzzle was sealed with a thin brass diaphragm. The O-Rings were 0.210 inch Neoprene. The following results were obtained:

| Pressure $lb/in^2$ | Velocity ft/sec |
|---|---|
| 100 | 141 |
| 150 | 221 |
| 200 | 274 |

In an effort to improve the efficiency of the gun, one piston was reworked to accommodate Neoprene O-Rings of 0.070 inch cross section. Test firings using this configuration (without evacuating the barrel) yielded the following results:

| Pressure $lb/in^2$ | Velocity ft/sec |
|---|---|
| 100 | 140 |
| 200 | 261 |
| 300 | 343 |

Both of the above firing series are plotted in Fig. 5 and both follow approximately the same curve, identified as curve "B."

In order to evaluate the foregoing experimental results against theoretical performance, the following evaluation was made.

The maximum theoretical performance of the gun is calculated assuming adiabatic expansion of the gas

with no friction losses. The work done by the gas on the piston is:

$$W = \frac{p_1 V_1 - p_2 V_2}{K - 1}$$

where $p$ = absolute pressure
$V_1$ = initial volume = 550 $in^3$
$V_2$ = final volume = 2245 $in^3$
$K$ = 1.4

Replacing $p_2$ by $p_1 (V_1/V_2)^K$

$$W = \frac{p_1 V_1}{K-1} \left[ 1 - (V_1/V_2)^{K-1} \right]$$

For values listed for $V_1$ and $V_2$:

$$W = 1.075\ p_1 V_1$$

Since the work of expansion equals the kinetic energy of the piston, the piston velocity is:

$$V_p = \sqrt{\frac{1.075\ (2g)\ p_1 V_1}{W_p}} = 22.4 \sqrt{p_1}$$

This velocity is plotted vs. reservoir pressure in Fig. 5 as the theoretical no-loss curve. It is seen that for pressures above 200 psig, the actual piston velocity measured with the 0.070 O-Ring configuration (Curve B) is consistently above 80% of the theoretical velocity. Extrapolation of Curve B indicates that a reservoir pressure of about 1200 psig will be required to achieve the desired piston velocity of 740 ft/sec.

## III. PROBLEMS ENCOUNTERED

Procurement of the air gun and procurement of the nozzle assembly were the primary problems encountered. Selection of the most suitable O-Rings for the piston was also a problem. However, these problems are now fully resolved.

The air gun was residual government property in the possession of a contractor who had completed all work associated with the gun. Pending release of the gun, Terraspace investigated several alternatives for use as a piston actuator. Immediately upon release of the gun, it was purchased and installed, and the nozzle design was finalized.

Several machine shops, which had earlier offered budgetary estimates on the nozzle assembly, responded with "No-Bids" or excessively high bids on the finalized nozzle design. Alternate sources had to be solicited. An order was placed with SPECO Division of Kelsey-Hayes Company in Springfield, Ohio on May 28, 1971, with delivery scheduled on or before August 31, 1971.

The former operator of the air gun recommended Teflon O-Rings on the pistons for a low coefficient of friction. O-Ring handbooks recommended 0.210 inch cross sectional O-Rings for reliable operation of 3.25 inch diameter pistons with linear or reciprocating motion. However, because of the hardness of the Teflon O-Rings, these recommendations were not optimum, and the piston design has been modified to use 0.070 inch Neoprene O-Rings.

## IV. FUTURE PLANS

The revised schedule for completion of tasks under the contract is given below:

| Task | Original Date | Revised Date |
|---|---|---|
| Test Rig Assembly | June 30, 1971 | Sept. 10, 1971 |
| Test Rig Checkout | July 31, 1971 | Sept. 10, 1971 |
| Rock Breakage Tests | Dec. 31, 1971 | Dec. 31, 1971 |
| Final Report | Jan. 31, 1972 | Jan. 31, 1972 |

Compression of the rock breakage test program into approximately 110 days is considered to be feasible because it was in the schedule for this task that the original Program Plan allowed for the most contingencies. All possible sub-tasks relating to the test rig are being completed prior to delivery of the nozzle assembly.

Dr. W. C. Cooley visited Prof. Voitsekhovsky in Novosibirsk on July 1 and 2, 1971 and it is planned to procure a Russian-manufactured nozzle as a back-up to the one being manufactured in the U.S. by Kelsey-Hayes. Delivery of the Russian nozzle is expected during August.

## V. CONCLUSIONS AND RECOMMENDATIONS

The contractor has concluded that:

1) The gas gun is a suitable actuator.
2) Neoprene O-Rings of 0.070 inch diameter are best for the gas gun piston.
3) Evacuation of the gas gun barrel is not warranted.

The demonstrated performance of the gas gun shows that it is possible to reach the test program objectives within safe design limits of the gun. Testing to date has been limited to 300 psi nitrogen pressure and velocities under 350 ft/sec only because it was not economically feasible to absorb higher energies without the nozzle assembly. Styrofoam proved to be an effective energy absorber but there was a practical limit to the total volume which could be inserted; a heavy wooden enclosure for the styrofoam failed several times under the radial pressures.

Neoprene O-Rings of 0.070 inch cross section were chosen for reasons shown in Paragraph II-F. Teflon O-Rings were ruled out for the following reasons:

1) Difficult to install
2) Time consuming installation
3) Low-pressure leakage
4) High compressive forces
5) High initial cost

If the application could derive benefit from the low coefficient of friction, a small saving in nitrogen consumption would be the only advantage.

A small improvement in gas gun performance was achieved by evacuating the gun barrel as reported in Paragraph II-F. However in order to evacuate the barrel a diaphragm must be installed at the gun muzzle. Both the diaphragm installation and the vacuum pump-down are time-consuming. The ruptured diaphragm center would also be carried along to the piston-water interface and add another variable in the test program. During some of the programmed highest pressure shots the nozzle will have to be evacuated; to accomplish this simultaneously with gun barrel evacuation would require either a second vacuum pump or manifold vacuum lines. Again, the only advantage would be a small saving in nitrogen consumption.

The contractor recommends continuation of the research program in accordance with the Future Plans in Section IV.

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13. ABSTRACT

The purpose of the research program is to optimize the efficiency of rock disintegration by pulsed high pressure water jets. The high energy pulsed jets are produced using an exponential nozzle (U.S. Patent 3,343,794). Actuation is provided by a steel piston, 3.25 inches in diameter, fired from an air gun. Results to date cover only the suitability and calibration of the air gun. The nozzle assembly is scheduled for delivery during the second half of the contract period, and the rock fracture tests will be conducted in that period. It is concluded that the air gun actuator is suitable for the intended use. Design data for the nozzle are presented.

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Disintegration, Rock | | | | | | |
| Jet, Liquid | | | | | | |
| Nozzle, Exponential | | | | | | |
| Air gun | | | | | | |